TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

FLOR TRYHOU

POWER QUALITY ISSUES IN A DISTRIBUTION GRID CAUSED BY SOLAR PV POWER GENERATION

Master of Science thesis

Examiner: Prof. Seppo Valkealahti
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ABSTRACT

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Distribution grids is evolving from centralized power generation to decentralized power generation. Solar PV power generation is widely spread and this has an impact on the distribution grid. The biggest impact is the possibility that overvoltages can occur during moments when the energy produced by solar panels is higher than the energy consumed. But also the effect of PV installations on voltage drops en transient overvoltages are described in this thesis.

Therefore, the impact of certain factors is described in this master's thesis. Some of those factors are discussed by using three different models. One model represents a rural area, the second represents a suburban area and the last one represents an urban area. Each of those models have a specif set of grid parameters to distinct them from each other. Other parameters are studied by only using the rural and the suburban models or using only the rural model.

Five influences on the voltage of the distributed grid are discussed. The first influence handles the grid impedance, there the importance of the differentiation in three types of area becomes clear. A next influence involves the impact of a fixed value of solar irradiation on the PV modules. Also the influence of a sudden change in solar irradiation, while the electric load is at its maximum, is covered in this thesis. The fourth parameter is the influence of the household lod for different weather conditions. The last parameter that is reported is the temperature of the PV modules.

It is interesting to understand how overvoltages behave. In some circumstances, when the overvoltage is too high, PV installations might get disconnected from the distribution grid. This can create unintented islanding and it can cost the owner money because he can't sell the energy to the energy company.

PREFACE

This master's thesis has been completed at Tampere University of Technoloy's in the Laboratory of Electrical Energy Engineering to obtain the degree of Master of Science Energy Engineering Technology.

I would like to thank my supervisor Professor Seppo Valkealahti for guidance and feedback during the process of completing this work. I am also grateful to Professor Valkealahti for providing me a topic that matches two of my fields of interest, being renewable energy and power quality. I also like to thank mister Philip Keersebilck from KU Leuven as he helped a lot with the administration that made it possible to go on Erasmus.

Tampere, 22.5.2018

Flor Tryhou

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AC	Alternating current
DC	Direct current
IND	Inductive
L1	Line 1
L2	Line 2
L3	Line 3
N	Neutral
MPPT	Maximum power point
MPPT	Maximum power point tracking
PV	Photovoltaic
RMS	Root-mean-square

Symbols

a	Ideality factor of a diode
I_0	Dark saturation current
I_{pv}	Current going through a PV cell
I_{ph}	Photocurrent
I_{SC}	Short-circuit current
k	Boltzmann constant
q	Charge of an electron
R_{ac}	Resistance under AC conditions
R_s	Series resistance
R_{sh}	Shunt resistance
T	Temperature
t	Time
V	Voltage
	V_{LN} Line to neutral voltage
V_{OC}	Open-circuit voltage
$\mathrm{V_{LN}}$	Line-Neutral voltage

1. INTRODUCTION

Energy is one of the major needs of society. Since the beginning of the industrial revolution, power has been produced by using fossil fuels. Growing population, limited fossil fuel resources and polluting energy production are causes why scientists have been developing more sustainable forms for energy production during the last decades. [7]

Solar energy is one of the renewable energy sources. The solar energy source is enormous compared to human's needs. The sun provides the earth's surface approximately 885 million terrawatthours of energy every year, that is 6,200 times the commercial primary energy consumed by humankind in 2008.

Figure 1.1 shows the amount of energy used by humans compared to the estimated total of fossil fuels left on earth and the annual energy the sun provides on earth.[8]

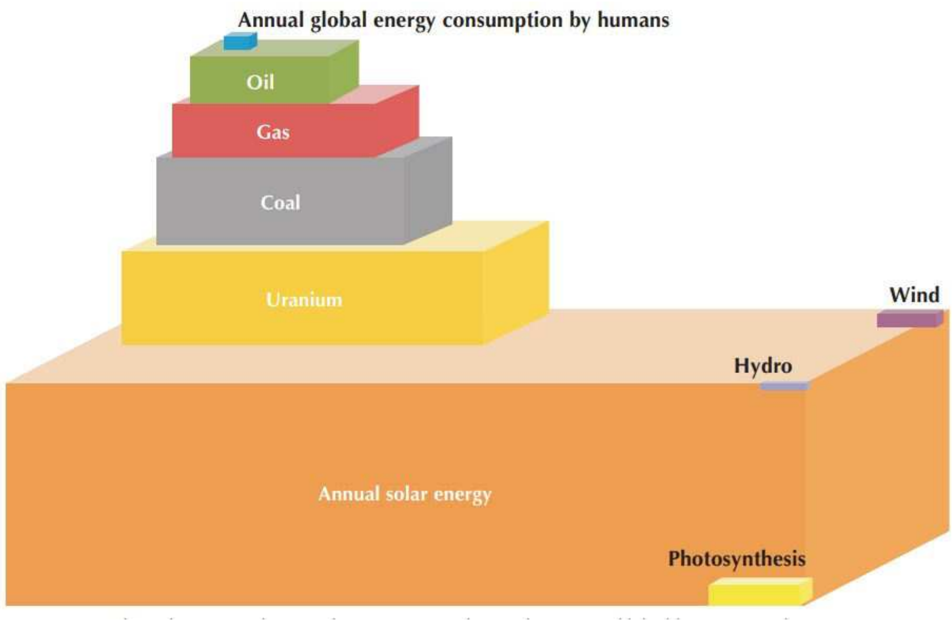


Figure 1.1 *Global energy consumption compared with different resources. For oil, gas, coal and uranium the estimated reserves are shown. The renewable sources are shown for one year. [1]*

Given these numbers, it is undeniable that solar energy will be more important in the future than it is today. The price of PV modules has always been decreasing. More or less in a decade, the prices were low enough for people so that solar energy became more widespread. [9]

Calculations of the classical distribution grids, with centralized power production are no longer entirely valid with increased PV power production. These grids are calculated for a power flow in only one direction. The possibility that current flows in two directions may cause overvoltages at places far from a transformer. Various parameters influencing this phenomenon are handled in this thesis. [10]

2. THEORETICAL BACKGROUND

In this chapter the basics of photovoltaic power production and essential concepts of power quality are explained. This information is necessary to completely understand what is described in this thesis.

2.1 Photovoltaic cells and their working principles

2.1.1 N-type and P-type semiconductor

A silicon atom has 14 electrons which are arranged in such a way that four valence electrons can interact with another atom. As a solid, silicon usually shares all of its valance electrons with other silicon atoms. No electrons can move freely in the solid in this case. Two other possibilities occur when some of the silicon atoms are replaced by a phosphorus or a boron atom.

Phosphorus atoms have five valence electrons. Combining phosphorus with silicon gives one spare electron, which can move freely around. This is an electron donor or N-type semiconductor. On the other hand, when silicon is combined with boron, there will be one electron short. This is because boron only has three valence electrons, the lack of an electron is called a hole. Silicon with boron as impurity is an electron acceptor or P-type semiconductor.

2.1.2 PN-junction

When a P-type and a N-type semiconductor are put together, the negative and positive charges move across the junction due to diffusion. Electrons that originate from the N-type will go to the P-type near the junction. Similar to this, holes move from the P-type towards the N-type. This will continue until it reaches an equilibrium. The equilibrium is reached as an electric field between the moved charges inhibits further diffusion. The electric field over the distance of the junction causes a voltage. This is where the photovoltaic effect comes in. A figure of the composition of a PN-junction with the valence band and the conduction band is shown in figure 2.1

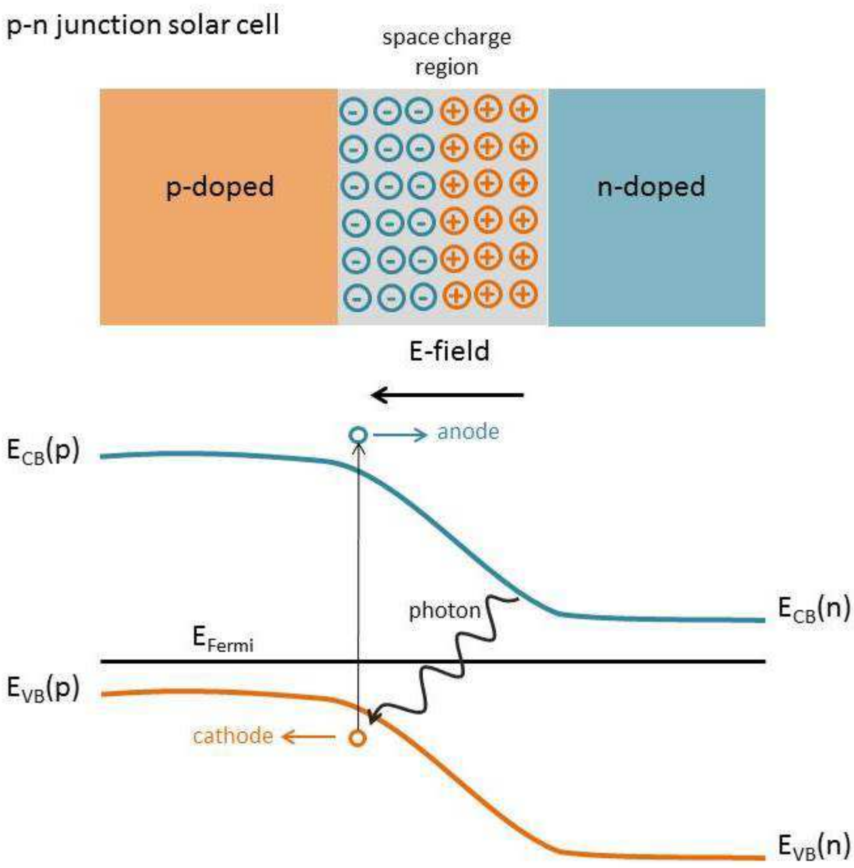


Figure 2.1 *A schematic view of a PN-junction and the band gap over the PN-junction [2]*

2.1.3 The photovoltaic effect

Light striking the P-side of the junction with enough energy will cause the formation of an electron-hole pair. The PN-junction inhibits holes to go from the P-side to the N-side, but it accelerates electrons that want to go in that direction. Now the electron from the electron-hole pair goes to the N-side and the hole remains in the P-side. For light striking the N-side something similar happens, but now it is the hole that moves to the P-side.

Connecting N-side and P-side by means of an external circuit will force an electric current to flow through the circuit. With this current flowing the earlier discussed equilibrium is maintained and as long as light gives energy to the cell, the current will keep flowing. [11]

2.1.4 Current-Voltage characteristics of a PV cell

The equation that describes the relation between the current and voltage of a PV cell is the following:

$$I_{pv} = I_{ph} - I_0(e^{\frac{qV}{akT}} - 1). \tag{2.1}$$

In this equation I_{pv} represents the current that exits in the PV cell. I_{ph} is the photocurrent, the value of this current depends on the solar irradiance. I_0 is the dark saturation current. T is the temperature in Kelvin, q is the charge of an electron, k represents the Boltzmann constant and a is the ideality factor of the diode. [12][13]

Efficiency under working conditions is also determined by the dissipation of power across internal resistances. These resistances can be modelled as R_s and R_{sh}. R_s is the series resistance in the equivalent circuit of the PV cell and R_{sh} is the shunt resistance in the same equivalent circuit. Their effect on efficiency will be described later on. Putting this all together results in the equivalent circuit of a photovoltaic cell as shown in figure 2.2.

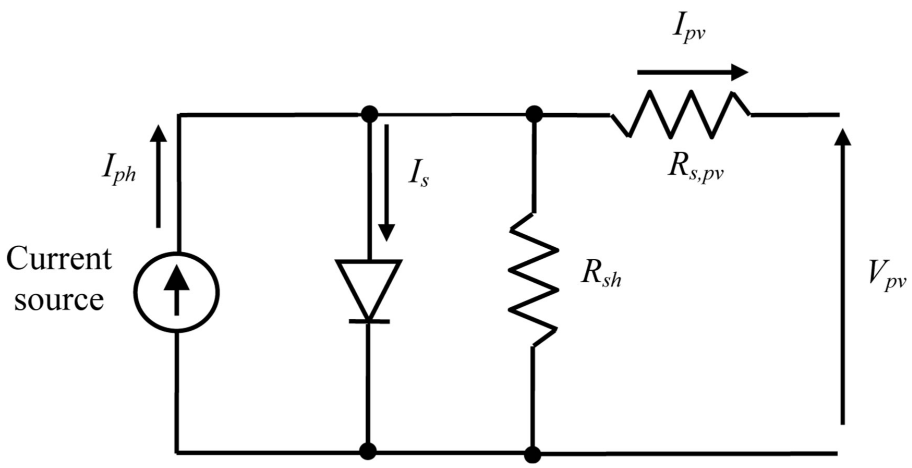


Figure 2.2 *Equivalent circuit of a PV cell. [3]*

Figure 2.3 shows the shape of current-voltage characteristics and power-voltage characteristics. Notice the linear increase of I_{ph} as function of the irradiance. V_{OC} also increases with irradiance, however, V_{OC} is far less influenced by irradiance than I_{ph} is.[14]

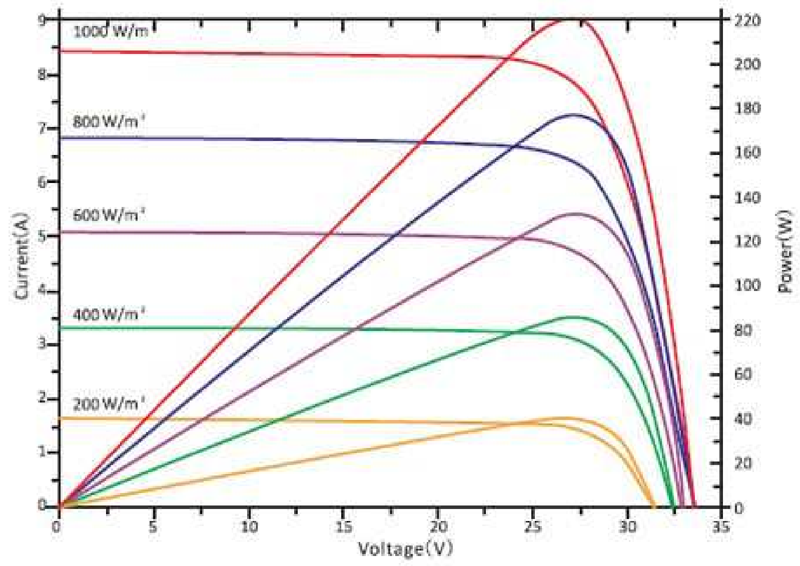


Figure 2.3 *Current and Power as function of voltage of a PV module for different irradiances.[4]*

2.2 Serial and parallel connection of PV module

PV cells are relatively small and have a low power output per cell. Therefore cells can be connected to each other in either series or parallel. Connecting cells in series increases the output voltage, while connecting them in parallel increases the current output. In the next part important consequences of the connections will be described.

2.2.1 Serial connection

Solar cells are designed to operate in the fourth quadrant of the IV characteristics, this means it is meant to produce power and not to consume power.

In ideal conditions, this means the same conditions for each cell, each cell has the same I_{sc}, V_{oc} and produces the same amount of power. In ideal circumstances, a connection in series of n cells equals n times the voltage output of one cell. Finally, the current of n cells remains the same as for one cell. The IV characteristics are shown for a single PV cell and for two PV cells connected in series in figure 2.4.

When one of the cells in a serial connection is (partially) shaded, the current that can flow is reduced. As a consequence of this, the current of the cells with full insolation is also reduced. This means that the total power produced is less than

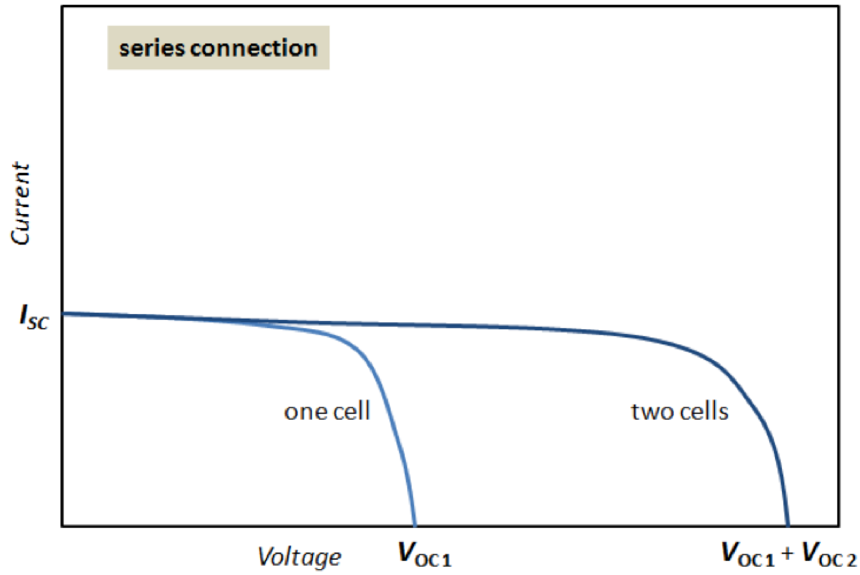


Figure 2.4 *Comparison of current as a function of voltage for a single PV cell and for two PV cells connected in series. [5]*

the sum of the power that each cell would be able to produce individually. This is visualized in figure 2.5.

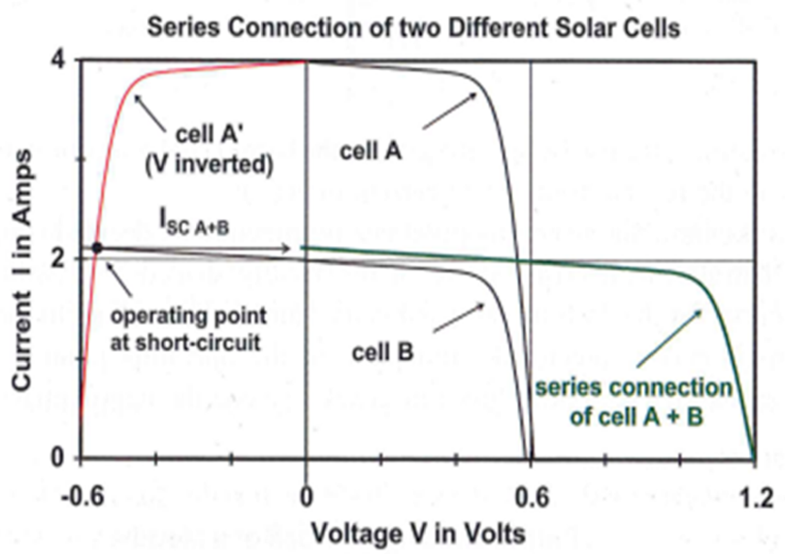


Figure 2.5 *Current as a function of voltage of two PV cells and their serial connection. [6]*

If the circuit with multiple cells, of which one or more are shaded, is short-circuited, the voltage over the shaded cells is reversed. This causes the PV cell to operate in the third quadrant, where it dissipates power generated by other PV cells. This is an undesired working condition which can be solved by placing a shunt diode over the PV cell.

2.2.2 Parallel connection

In ideal circumstances parallel connection of PV cells increases the output current and power, while the voltage remains the same. For n cells the current and power of one cell are multiplied by n. Of course, which is also valid for serial connection, multiplying by n is actually a little less. This is due to losses caused by connection losses, manufacturing tolerances, installation, etcetera. Figure 2.6 shows the impact of a parallel connection on the IV characteristics.

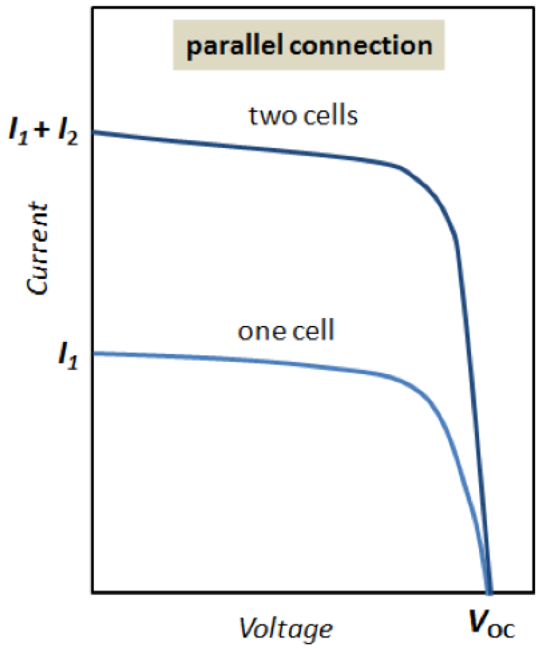


Figure 2.6 *Comparison of current as a function of voltage for a single PV cell and for two PV cells connected in parallel. [5]*

If a parallel connected cell is shaded, it can act as a load under certain circumstances. This leads to power losses and the efficiency of the system drops drastically.

2.3 Power quality issues

In this section power quality issues that occur frequently are listed. Photovoltaic power production will be linked to each of these problems in the next section. [13][15]

2.3.1 Voltage dips and drops

Dips refer to the momentary decrease in the RMS voltage amplitude for durations varying from half-cycle to 1 minute. During the dip, voltage drops to a value under 90% of the nominal voltage. At least 1 % of the nominal voltage should be maintained, when the voltage drops below 1 % of this value, it is considered to be a voltage interruption.

Causes of dips are faults on the power system and the starting of large loads. Also the loss of power generation can be a possible cause. The main idea behind this is the need to produce the same amount of power as the amount of power that is consumed. When the demand is higher than the production, voltage dips occur.

While the terminology of voltage dips is used for a temporary decrease of voltage, voltage drops are used when the voltage depends on the location. Due to the impedance of power distribution cables, voltage drops occur over those cables.

2.3.2 Voltage swells and rises

Voltage swells may exist for the same time as voltage dips, but in this case voltage rises. An increase of at least 10 % is necessary to speak of a voltage swell. Actions that cause swells are switching of large loads and producing more power than needed.

A distinction can also be made if the voltage depends on time or location. Swell is typically used for temporary events, while voltage rise is used if the voltage depends on the location. The rise happens also as a consequence of the impedance of the power distribution cables, only the voltage rises when the current flows in the opposite direction compared to a voltage drop.

2.3.3 Harmonics

In most cases, supply voltage is assumed to be a perfect sine. However, often this sine is polluted with sines of other frequencies. A distinction is made concerning harmonics. The first type are frequencies that are integer multiples of the fundamental frequency. Secondly, harmonics that are not integer multiples also exist. These latter are called interharmonics. Harmonics are mainly caused by nonlinear loads. Other origins may be external events as lightning.

2.4 Power quality issues related to PV power generation

The power generated by PV cells is DC. To be widely accessible and to connect it to the distribution grid, the power supply needs to be converted to AC. Firstly the produced DC voltage is risen by a boost convertor. Also MPPT is implemented so the PV module is able to work at its highest efficiency. When the DC voltage reaches the correct level, it can be converted to AC by an inverter. This is possible in single phases execution and in three phase execution.

2.4.1 Voltage dips and drops

Voltage drops linked to PV power generation do not exist as a consequence of faults. They do exist as weather circumstances change rapidly. The amount of power generated depends on the irradiance [W/m^2] of the sun on solar panels. In only is matter of seconds, or even less, power production can change from full power generation (clear sky) to only a fraction of its initial value (heavily clouded).

As mentioned above, voltage dips exist due to an imbalance between production and demand. Traditional power plants cannot adapt fast enough to catch these varying circumstances. Therefore, voltage dips often occur. Voltage drops are not an issue since the voltage drops have been taken into account when designing the distribution grid.

2.4.2 Voltage swells and rises

Voltage swells have the same origin as voltage dips, rapidly changing weather conditions. The difference is the direction of change. Swells occur when weather changes from heavily clouded to clear sky. Also rises will be induces if the swell lasts for longer moments and don't adapt to the direction of current.

Many factors affect the height of the dip or swell. Slew rate of irradiance, total load of the distribution grid, grid impedance, penetration level of PV power on the grid, grade geographically distributed PV power generation, etcetera are only some of the factors. And only some of them will be evaluated in this thesis.

2.4.3 Harmonics

PV generators are connected to the distribution grid through power electronics, these power electronic devices have a non-linear character. Inverters are in some cases the cause of harmonics. A lot of devices are sensitive to harmonics, among them also the inverters that cause the harmonics.

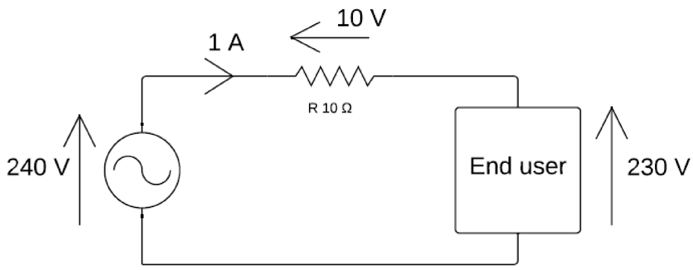
2.5 Voltage swells in rural areas due to PV power generation

In this section the basic concept for voltage swells in rural areas due to solar PV power generation will be presented using two figures. As described in the introduction distribution grids are designed for centralized power production.

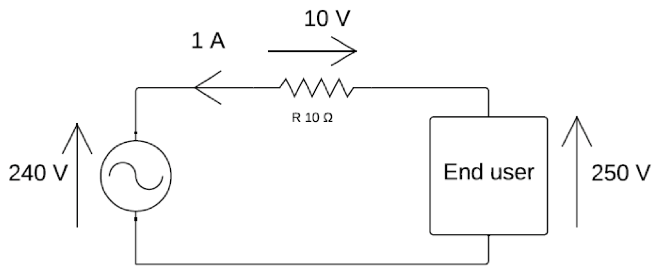
To meet the requirements of the EN 50160 standard supply voltage must be within a 10% range of the nominal voltage. [9] To accomplish this for each point in a distribution grid, also for points at the end of the distribution line, the nominal voltage for the transformer is set a little higher. The nominal voltage of the transformer in figure 2.7(a) is set at 240 V. The voltage drop over the distribution cable caused by a power flow from the transformer to the consumer results in a nominal voltage at the consumer of 230 V.

With distributed power generation nowadays, the scenario presented in figure 2.7(b) also belongs to the possibilities. The transformer is still set to 240 V. The power, however, flows in the opposite direction of case a. The current flowing to the transformer also causes a voltage drop over the distribution cable, but now the consumer (which is a producer in this case) operates at a voltage higher than the voltage set at the transformer, in this case 250 V.

When the voltage gets too high, the solar power production will be disconnected from the distribution grid. Customers have contracts with power suppliers and can get money for the power that they produce. As customers get disconnected at moments where the solar power production is at its peak, they get less money compare to people living closer to the transformer. Therefore it is important to get grip on those overvoltages and also have detailed information on what factors have an influence on those overvoltages.



(a) If the end user does not produce energy or produces less than he consumes, then the voltage at the end user will be lower than the voltage at the distribution transformer.



(b) If the end user produces more energy than he consumes, then the voltage at the end user will be higher than the voltage at the distribution transformer.

Figure 2.7 *Two figures that are a simplified illustration of how overvoltages are able to occur.*

3. SIMULINK MODELS

In this chapter the models will be discussed that were used to obtain the results described in the next chapter. The PV installation will be discussed first and after that three models will be introduced.

3.1 PV installation and load

3.1.1 Overview

As the models in the next section show, each location that represents a house or a housing block, exists of a modeling block that represent the PV installation and a household load. This section provides the necessary explanation about this structure. The model exists of four main parts: PV array, inverter, inverter control and load.

3.1.2 PV array

This is not a complex part to simulink, but it has a lot of opportunities. Figure 3.1 shows that two inputs can be given to the PV array. The temperature can be set as a fixed value for the entire simulation. Secondly, the irradiance on the PV array can be set on either a fixed value or to multiple values changing during the simulation.

In the "PV Array"-block multiple settings are possible. There is data available for multiple types of PV modules. As one type is selected, automatically the typical characteristics of the module are set. This are the values for maximum power, V_{OC}, I_{SC} and some other values defining the exact Voltage-Current characteristics with a given irradiance and temperature.

As an Array is built of multiple modules, it is also possible to define the amount of series-connected modules per string and how many strings that are connected in parallel.

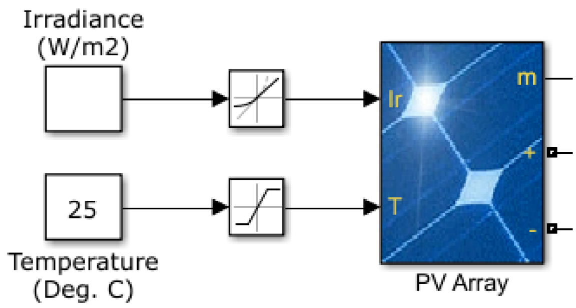


Figure 3.1 *PV array in Simulink.*

3.1.3 Inverter

Figure 3.2 is the inverter. The power produced with solar energy is DC power. The distribution grid uses AC power, therefore the DC should be inverted to AC. *A* and *B* on the figure are the connections for the AC power, while *g* is the input from the inverter controller.

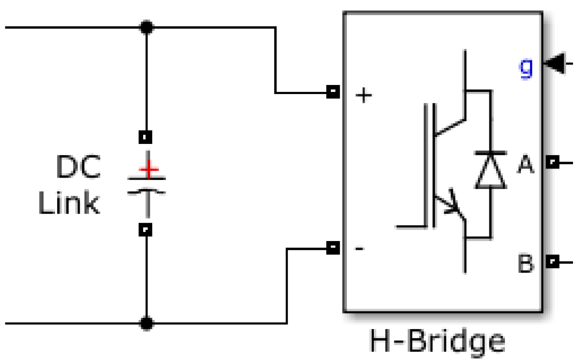


Figure 3.2 *H-Bridge in Simulink.*

3.1.4 Inverter control

The inverter control is built using five major blocks. These blocks are clearly visible in figure 3.3.

The first one is the MPPT controller and uses the perturb and observe method. This is a good method for steady state conditions to operate at the highest efficiency, but the downside is a slow response for rapid changes in irradiance. The MPPT

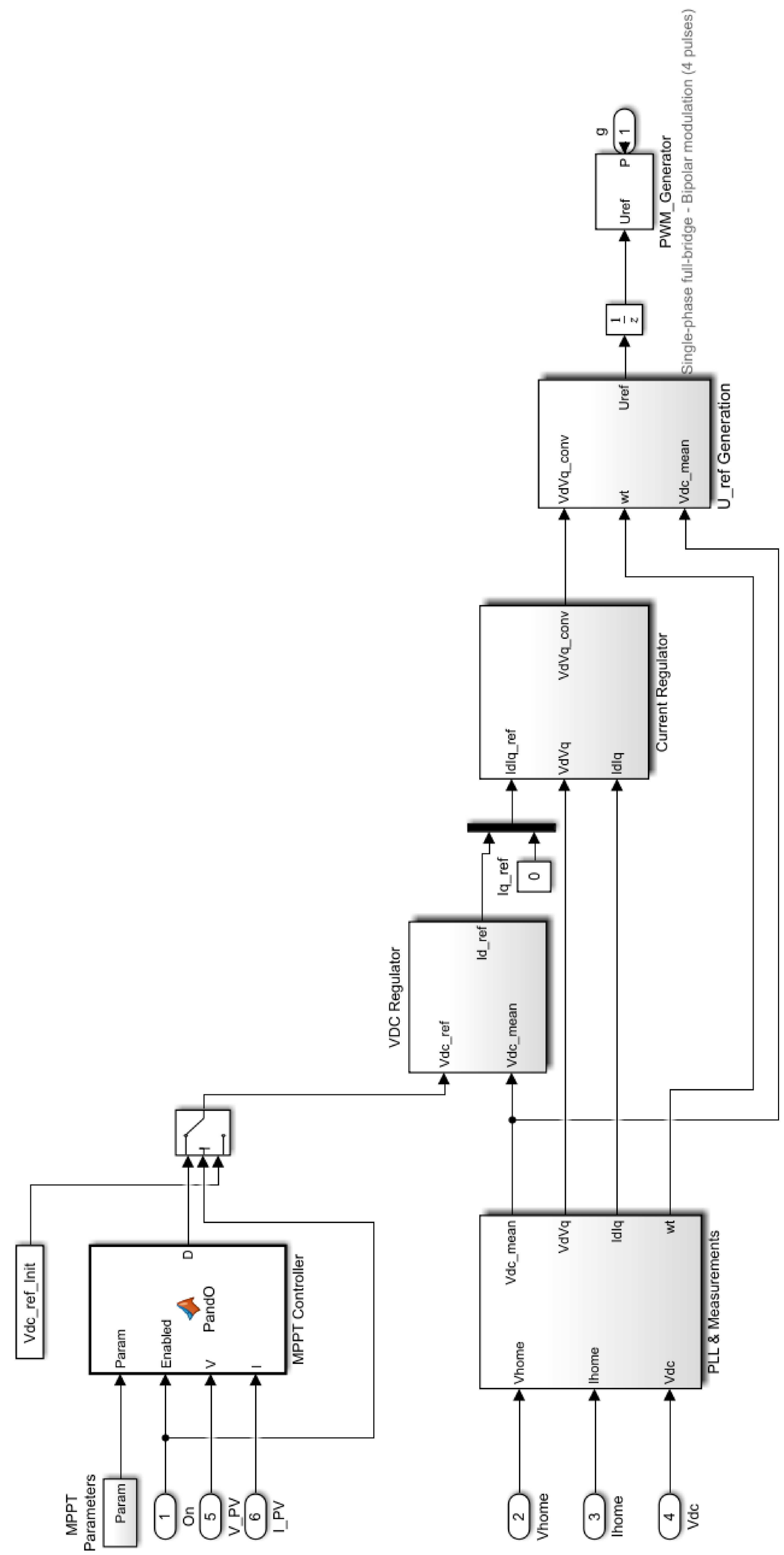


Figure 3.3 *Inverter Control in Simulink.*

controller regulates the reference DC voltage signal of the inverter to get a DC voltage giving the maximum power from the PV array.

Secondly, the VDC regulator determines the required active current (I_d on figure 3.3) for the current regulator. The current regulator is the third subsystem. It uses the determined active current from the previous step and a reactive current, which is here set at 0 A, to determine the required reference voltages for the inverter.

The one but last part is the PLL and measurements part. This block assures the synchronization and the measurement of the voltages and currents. The last part is the PWM generator which generates the carrier frequency for the PWM bipolar modulation to regulate the switching of the IGBTs.

3.1.5 Household Load

The load consists of a resistance and an inductance. This is no part of the PV installation, but is used to simulate all the loads of a household. Using a combination of the resistance and inductance, the power and power factor can be set at the wanted values. A typical one family household in Belgium can use approximately 7.5 kVA during peak hours. This is why the maximal electrical household load used in simulations is set at this value.[16]

3.2 Distribution grids for different areas

It is very hard, if not impossible, to model an average distribution grid. Therefore three different models were used during this paper. Each of these models is supposed to represent an area that is differently populated than the other two models described. Those areas will be referred to as rural, suburban and urban areas. Hereby is the rural area the least densely populated and the urban area the most densely populated area.

3.2.1 Rural area

For rural areas the model shown in figure 3.4 is used. Of course in real situations more than 9 houses will be fed by one transformer. This model, and the next ones, represent only 9 consumers to reduce the computing time.

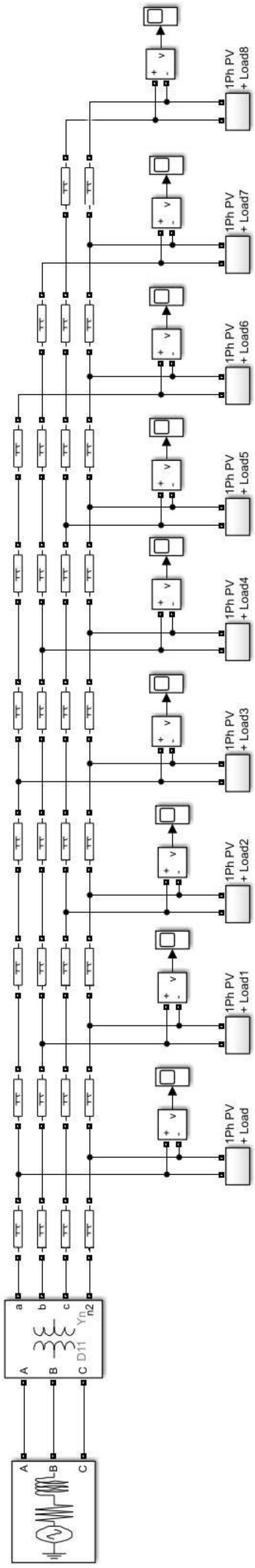


Figure 3.4 *Simulink model for rural areas.*

Different parts can be recognized on this model. To start the medium voltage distribution power source is used and coupled to a distribution transformer. The source operates at a voltage of 14 kV which is transformed to 400 V, both line-to-line voltages. Secondly, 33 sections of distribution cables are used in this model. This are crucial parts in the models, the voltage drop causing overvoltages will be over this parts. Next to the scopes, which register the voltage at each moment, the last parts are the blocks representing the solar PV installations and loads of the households. More detailed information about the PV installation modelling is written in the next section.

Note that every consumer is only connected to one phase in this case. The power supplier also wants the load of the grid to be as symmetrical as possible. For this reason, neighbors are connected to different lines. The choice to work with single phase connections is based on the Belgian distribution system. Households are almost always connected to only one phase.

Exact parameters of all those blocks are not given in a table in this section. The reason for this is that most parameters varied for different simulations. Therefore, the parameters are mentioned together with the results. At this point it is enough to think about the scale of PV installations and consumer loads in rural areas. In rural areas, people tend to live in houses and not apartments. This means that the loads used in the model will be for only one household, assuming the house is not a farm. There is also enough space to place as much solar PV panels as needed or wanted by each house. This is different in urban areas. Finally, the distribution cables are considerably longer than in suburban or urban areas.

3.2.2 Suburban area

The same model is used for suburban areas as for rural areas. However, parameters will be fundamentally different. People also live in houses instead of apartments, however, some small apartment blocks are found in suburban areas, this small apartment blocks have a higher energy consumption than one house. Space for PV installations is still no issue, except for small apartment blocks. Also, distribution cables are shorter than in rural areas, but still longer than in urban areas.

3.2.3 Urban area

For urban areas, the model used is presented in figure 3.5. The three power lines each go in another direction and use a seperate neutral line. The total length of each line is much shorter than in rural and suburban areas.

3.3 PV installation and load

The PV array and load are set in the model as shown in figure 3.6. They are both placed in the same block because they are both on the consumer end of the connection to the grid. As mentioned earlier, the household load varies from 0 kVA to approximately 7.5 kVA.

As the average annual electrical energy consumption per household is 3,353 kWh in Belgium, the dimensioning of the PV installation uses the rule of thumb to multiply this annual energy consumption by 1,1. The maximum power generation of the used PV installations is around 3,688 Wp. The real value used is a little higher because an integer amount of PV solar panels should be used in an installation.

In all the simulations the used solar panels are *Trina Solar TSM-250PA05.08*. These panels have a nominal power 249.89 Wp, therefore 15 of these panels are used in each household to reach the desired power of 3748.35 Wp. Information of these particular solar modules is given in the table below.

Table 3.1 *Information about the Trina Solar TSM-250PA05.08 solar PV panel.*

Characteristics	Value	Unit
Maximum power	249.86	W
V_{oc}	37.6	V
Voltage at MPP	31	V
Cells per module	60	
I_{sc}	8.55	A
Current at MPP	8.06	A

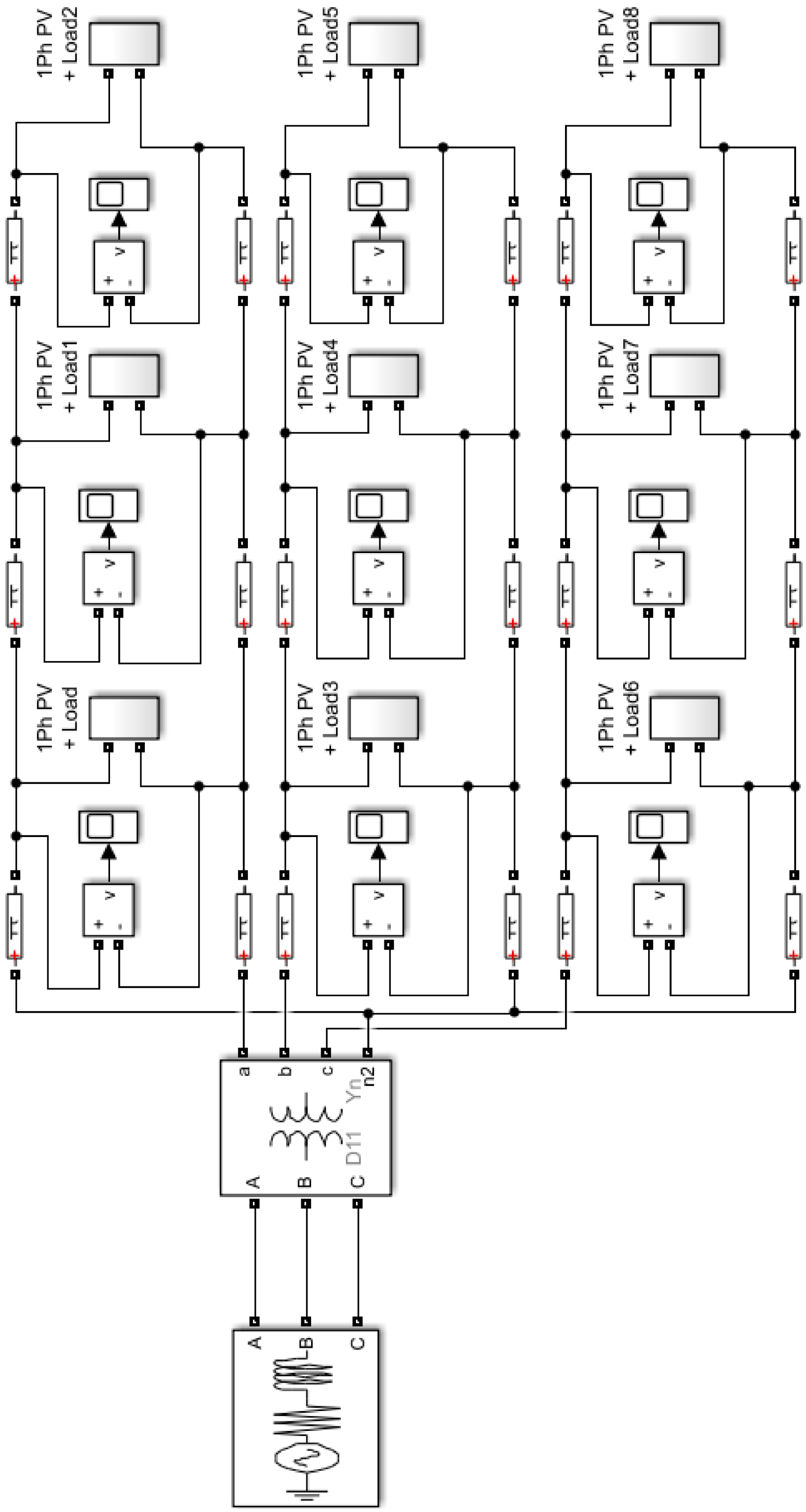


Figure 3.5 *Simulink model for urban areas.*

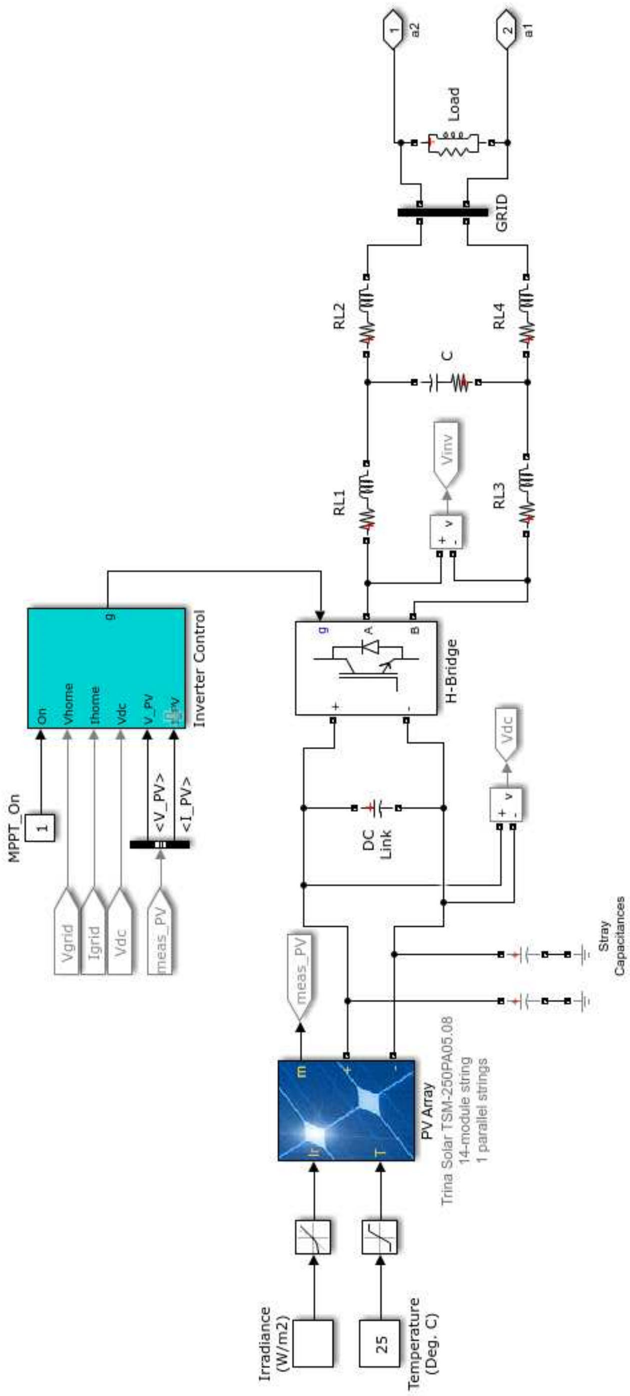


Figure 3.6 *Single-phase transformerless Grid-Connected PV Array.*

3.4 Simulations

In the following sections, the simulations are listed as well as the parameters used for each simulation. It should be noted that all the parameters are equal for each household. This uniformity makes it possible to get results in a structured manner and the results are more visible.

3.4.1 General parameters

In some simulations, irradiation on the PV modules will vary and in each of this simulations this variation will be simulated 0.4 seconds after the simulation has been started. This assures that the entire system has time to overcome transient responds at the start of the simulations. Households also don't have power factor improvement so in all simulations an inductive power factor 0.9 is used.

Table 3.2 shows information about the distribution cables that are used for the simulations. Table 3.2 shows the data of 3 distribution cables. The first one is the minimal cross section of the distribution cable required for the current that could run through it. The next two are the next two commonly buyable cross section areas.

Assuming the overcurrent protection of each household makes it possible to get 40 A and three households are connected to one phase, the distribution cable should be able to endure 120 A. Using correction factors for the underground placement, the minimum cable cross section is 50 mm^2. The next two commonly used cross sectional areas for distribution cables are 70 mm^2 and 95 mm^2. The data used are valid for cables from the manufacturer Eupen of the XVB type that are suitable for voltages up to 1 kV. The parameters of the distribution cables are the inductance and R_{ac} at 90 °C. R_{ac} is the value of the resistance of the cable under AC conditions. AC is especially mentioned because the value the resistance under AC conditions is slightly different than the value under DC conditions

Table 3.2 *Parameter values of the different distribution cables used for the different simulations.*

Cross section (mm^2)	**R_{ac} at 90 °C (Ohm/km)**	**Inductance (mH/km)**
50	0.494	0.253
70	0.343	0.249
95	0.247	0.244

A fixed parameter for all simulations is the distance between households in each type of area. As can be seen on figures 3.4 and 3.5, the distribution cables are divided in segments. The length of each segment is given in table 3.3.

Table 3.3 *Length of each distribution cable segment for different types of areas.*

Area	length (m)
Rural	200
Suburban	50
Urban	20

3.4.2 Influence of grid impedance

The first simulations are used to show the influence of the impedance of the grid. Therefore solar irradiation is set at 0 W/m^2. The household loads are set at the value for peak hours and the three different cross sections of distribution cables are used. Table 3.4 provided the fixed values during the simulations.

Parameter	Value	Unit
Solar irradiation	0	W/m^2
PV array temperature	25	°C
Household load	7.5	kVA
Power factor	0.9 IND	

Table 3.4 *Parameters used to show the influence of the grid impedance.*

3.4.3 Influence of weather conditions

For further simulations the smallest cross section will be used. Referring to the weather conditions as in previous chapters and sections, the first simulations were in circumstances with no solar panels or in dark conditions. For the next simulations, various weather conditions will be evaluated under static circumstances, which means that the solar irradiation will still be constant during the entire simulations.

Solar irradiation of 1000 W/m^2 gives the maximum power output and goes hand in hand with a sunny, cloudless sky. To compare the influence of the weather, results obtained by the simulations discribed in 3.4.2 will be compared with very good weather and a situation with a solar irradiation of 500 W/m^2, which will be referred to as average weather. Table 3.5 shows a summary of the settings.

Table 3.5 *Parameters used to show the influence of the weather conditions (500 W/m^2 for average weather and 1000 W/m^2 for good weather).*

Parameter	**Average weather**	**Good weather**	**Unit**
Solar irradiation	500	1000	W/m^2
PV array temperature	25	25	°C
Household load	7.5	7.5	kVA
Power factor	0.9 IND	0.9 IND	

3.4.4 Influence of changing weather conditions with maximal household load

In contrast to the previously described situations, this section envolves a change of weather condition during the simulations. To study the effect of varying weather conditions two situations should be evaluated. The first is an increase in solar irradiation, while the second one covers a decrease in solar radiation. Results of these simulations can be used to evaluate two relations between changing weather and supply voltage. The first parameter to be looked into is the size of the irradiation change and the second one is the direction of change.

For changing weather conditions the steps between levels of solar irradiation should be smaller than in the previous section so more results will be obtained. The parameters for the simulations are given in tables 3.6 and 3.7.

Table 3.6 *Parameters used to show the influence of change in weather conditions when the solar irradiation on the PV installation increases.*

Parameter	**Small increase**	**Medium increase**	**Large increase**	**Unit**
Solar irradiation before change	0	0	0	W/m^2
Solar irradiation after change	250	500	1000	W/m^2
PV array temperature	25	25	25	°C
Household load	7.5	7.5	7.5	kVA
Power factor	0.9 IND	0.9 IND	0.9 IND	

Table 3.7 *Parameters used to show the influence of change in weather conditions when the solar irradiation on the PV installation decreases.*

Parameter	**Small decrease**	**Medium decrease**	**Large decrease**	**Unit**
Solar irradiation before change	1000	1000	1000	W/m^2
Solar irradiation after change	750	500	0	W/m^2
PV array temperature	25	25	25	°C
Household load	7.5	7.5	7.5	kVA
Power factor	0.9 IND	0.9 IND	0.9 IND	

3.4.5 Influence of household load for different weather conditions

In the previous section the changing weather conditions were assumed to happen while all households have a electrical load of 7.5 kVA. It may also be interesting to look at what happens if households operate under lower loads to no loads. Therefore, simulations ran in 3.4.3 are compared with simulations using the same changes of weather conditions and using other loads. The loads used are 0 kVA, 2.5 kVA and 5 kVA.

3.4.6 Influence of PV module temperature

A last parameter that is being studied is the temperature of the PV module. Until now, the temperature was always assumed to be 25 °C. The influence of temperature is viewed in the same context as section 3.4.3. Weather conditions do not change during the simulations.

Temperature is set at 0 °C and 50 °C for both average and good weather conditions. This is done for the solely purpose to understand the influence of the temperature, the possibility of occurrence of a certain combination of weather and temperature is unquestioned. Tables 3.8 and 3.9 indicate the parameters for the executed simulations.

Table 3.8 *Parameters used to study the influence of the temperature of the PV module under different weather conditions (500 W/m^2 for average weather and 1000 W/m^2 for good weather).*

Parameter	**Average weather**	**Good weather**	**Unit**
Solar irradiation	500	1000	W/m^2
PV array temperature	0	0	°C
Household load	7.5	7.5	kVA
Power factor	0.9 IND	0.9 IND	

Table 3.9 *Parameters used to study the influence of the temperature of the PV module under different weather conditions (500 W/m^2 for average weather and 1000 W/m^2 for good weather).*

Parameter	**Average weather**	**Good weather**	**Unit**
Solar irradiation	500	1000	W/m^2
PV array temperature	50	50	°C
Household load	7.5	7.5	kVA
Power factor	0.9 IND	0.9 IND	

4. RESULTS

4.1 Influence of the grid impedance

The parameters from table 3.4 were used for the three different types of residential areas. The obtained results are mentioned in tables 4.1 to 4.3 . Because the conditions did not change during the simulation, all values of voltages are RMS values. The voltages V_{LN} are line to neutral voltages because single phase consumers are modelled.

Table 4.1 *RMS values of the voltage at the beginning (near transformer) and at the end of the power cable of all three phases with no solar irradiation and with a 7.5 kVA household load for three different distribution cables in a rural area.*

Cable cross (section mm^2)	**Line**	**V_{LN} near transformer (V)**	**at end of the cable (V)**
50	L1	212.1	189.1
	L2	202.2	177.2
	L3	194.3	162.5
70	L1	214.2	197.3
	L2	206.6	188.3
	L3	200.1	175.2
95	L1	215.8	203.1
	L2	209.8	195.4
	L3	204.6	185.2

The grid impedance plays a very important role in voltage drops and overvoltages. Tables 4.1 to 4.3 show that the voltage drop over the distribution cable increases with a decreasing cross section of the distribution cable. This is the case for either rural, suburban and urban areas. This is the expected result, the reason for this is the impedance of the distribution cable. The inductive part of the impedance slightly decreases with an increasing cross section, but as known from Pouillet's law, the resistive part of the cable impedance is inversely proportional to the square of the cross section of the cable. Therefore, the influence of the impedance is the most significant with the lowest cross sections of distribution cables.

Table 4.2 *RMS values of the voltage at the beginning (near transformer) and at the end of the power cable of all three phases with no solar irradiation and with a 7.5 kVA household load for three different distribution cables in a suburban area.*

Cable cross (section mm^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
50	L1	218.1	212.1
	L2	215.2	208.4
	L3	212.2	201.9
70	L1	218.6	214.3
	L2	216.6	211.4
	L3	214.3	206.9
95	L1	218.8	215.8
	L2	217.4	213.4
	L3	215.6	210.0

Table 4.3 *RMS values of the voltage at the beginning (near transformer) and at the end of the power cable of all three phases with no solar irradiation and with a 7.5 kVA household load for three different distribution cables in an urban area.*

Cable cross (section mm^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
50	L1	221.9	219.6
	L2	221.9	219.6
	L3	221.9	219.6
70	L1	222.6	220.9
	L2	222.6	220.9
	L3	222.6	220.9
95	L1	223.1	221.7
	L2	223.1	221.7
	L3	223.1	221.7

The voltage drop does is not only influenced by the cross section of the cable. Regardless of the cross section, the voltage drops in rural areas is much higher than in suburban or urban areas, with the voltage drop being the lowest in urban areas. This is also explainable using Pouillet's law, the resistance of a cable is directly proportional to its length. The models for all areas use a fixed length through this thesis. The length of the distribution cables, as stated in table 3.3, is the longest in rural areas and the shortest in urban areas.

This leads to important insights when overvoltages or voltage drops occur and the voltage does not meet the requirements for overvoltages or voltage drops as required by EN 50160 anymore. There are two options if the voltage does not meet the standard by exceeding the limits only a little. The first option is situated in a rural area, if the cross section of the distribution cable is rather small, then increasing the cross section could solve the problem. This can either be done by removing the existing distribution cable and replacing it with a bigger one, or the distribution grid operator can install an extra parallel cable next to the existing one. The second possibility is when the same problem happens in an urban area. The impedance in the urban area is already low because of the short distances. Replacing the distribution cable or adding an extra one will only have a minor effect. In the second case, the requirements of EN 50160 will still not be met.

4.2 Influence of weather conditions

The results of the simulations explained in 3.4.3 are meant to be compared with the results of the previous section. These results are used to check the influence of the weather conditions on the overvoltages or voltage drops at the end of the distribution cable. The results are shown in three tables. Table 4.4 provides information about the rural area, while table 4.5 shows the results for the suburban area and table 4.6 for the urban area.

Table 4.4 *RMS values of the voltage at the beginning (near transformer) and at the end of all three phases with 7.5 kVA household loads and a 50 mm^2 distribution cable for 500 W/m^2 and 1000 W/m^2 solar irradiation in a rural area.*

Solar irradiation (W/m^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
500	L1	214.8	196.5
	L2	206.7	188.9
	L3	201.1	176.8
1000	L1	217.0	203.1
	L2	211.0	197.0
	L3	206.1	190.9

Table 4.5 *RMS values of the voltage at the beginning (near transformer) and at the end of all three phases with 7.5 kVA household loads and a 50 mm^2 distribution cable for 500 W/m^2 and 1000 W/m^2 solar irradiation in a suburban area.*

Solar irradiation (W/m^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
500	L1	218.8	214.2
	L2	216.9	212.0
	L3	214.2	206.3
1000	L1	219.7	216.1
	L2	217.8	215.3
	L3	216.3	210.4

Table 4.6 *RMS values of the voltage at the beginning (near transformer) and at the end of all three phases with 7.5 kVA household loads and a 50 mm^2 distribution cable for 500 W/m^2 and 1000 W/m^2 solar irradiation in an urban area.*

Solar irradiation (W/m^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
500	L1	222.7	220.7
	L2	222.7	220.7
	L3	222.7	220.7
1000	L1	223.1	221.8
	L2	223.1	221.8
	L3	223.1	221.8

Good weather conditions, which result in a high solar irradiation on the PV installation, are beneficial for the grid operator when there is large electrical energy consumption. When each household has an electrical load of 7.5 kVA, like in the results above, the PV installation is not able under any circumstances to produce as much energy as the household consumes.

If the analogy with figure 2.7 is made, then the grid operates like in condition A under any weather condition. This means that there is a voltage drop and not an overvoltage. When the irradiance is higher, the energy produced by the PV installation also is higher. The current still flows from the distribution grid to the consumer, but the value of this current will be lower. With this lower current, the voltage drop will also be limited, so the grid operator will be less concerned to have an excessive voltage drop.

With maximal electrical household loads, the voltage drop in the simulations is reduced with 40 % if the situation of a solar irradiation of 1000 W/m^2 is compared to the situation without solar irradiation. When the voltage drops are expressed as a fraction of the nominal voltage, then it is clearly visible that rural areas are more vulnerable to voltage drops under different weather conditions than suburban and urban areas.

4.3 Influence of changing weather conditions with maximal household load

Since the difference between the suburban area and the urban area are small in comparison with the difference between the rural area and the suburban area, the latter two are the only ones of whom the results are included. Tables 4.7 to 4.10 show respectively the voltages for an increase of solar irradiation in rural areas, an increase of solar irradiation in suburban areas, a decrease of solar irradiation in rural areas and a decrease of solar irradiation in suburban areas.

The size of a sudden increase or decrease of solar irradiation on the PV modules does not affect the steady state value of the voltage after the change. It does not matter if the irradiance increases from 0 W/m^2 to 250, 500 or 1000 W/m^2. The end value of the voltages is the same as if it would be if the irradiance would be constant for an infinite amount of time. The same applies for a decrease from 1000 W/m^2 to 750, 500 or 0 W/m^2.

However, when the value of the irradiance suddenly changes, there is a short period where transients occur. On that moment, the distribution grid is adapting to the new situation by controlling systems that have a certain response time. If the solar irradiation gets higher, the peak value of the voltage will then go temporarily higher than the peak value of the steady state. The higher the sudden increase of irradiance is, the higher the peak value of the voltage during the transients. On the opposite side, when a sudden decrease of irradiance occurs, the peak value of the transients will be lower than the steady state value of the voltage. The bigger the difference in solar irradiation, the lower the transient peak value will be.

These peak values differ for all three distribution lines. A reason for this is that in each simulation the change of irradiance occurred after 0.4 seconds for all PV panels simultaneously. The distribution grid exists of three phases and each phase operates at 50 Hz. The three phases are shifted in time from each other. The time difference between the phases is one third of 20 milliseconds. This means the momentary value of the voltage is different for each line when the difference in irradiance takes place.

The timing of the change in power production affects the transient response. Therefore, this transients should be studied more in detail, so the voltage overshoots or voltage dips could be minimized. Also due to the grid impedance, an always returning reason, the difference between the peak height of the transient response and the peak height of the steady state value is higher at the end of a power line than at the beginning of it.

Table 4.7 *RMS values of the voltages in Volt at the begin and at the end of the line before and after an increase of solar irradiation in a rural area. The household load used is 7.5 kVA and the cable cross section is 50 mm^2.*

Phase	**Begin (B) or End (E) of line**	**Small increase**		**Medium increase**		**Large increase**	
		t<0.4 s	**t>0.4 s**	**t<0.4 s**	**t>0.4 s**	**t<0.4 s**	**t>0.4 s**
L1	B	211.5	213.2	212.0	214.1	212.1	216.5
	E	190.4	192.1	189.5	195.4	189.3	202.4
L2	B	203.3	204.3	202.6	206.4	202.2	210.7
	E	179.2	182.0	179.0	187.8	179.2	198.8
L3	B	196.2	197.3	194.6	200.6	194.5	205.6
	E	162.6	167.8	162.6	174.8	167.7	187.7

Table 4.8 *RMS values of the voltages in volt at the begin and at the end of the line before and after an increase of solar irradiation in a suburban area. The household load used is 7.5 kVA and the cable cross section is 50 mm^2.*

Phase	**Begin (B) or End (E) of line**	**Small increase**		**Medium increase**		**Large increase**	
		t<0.4 s	**t>0.4 s**	**t<0.4 s**	**t>0.4 s**	**t<0.4 s**	**t>0.4 s**
L1	B	218.0	218.3	218.5	218.7	217.8	219.5
	E	211.8	212.9	211.7	213.8	211.9	215.7
L2	B	215.7	215.8	215.4	216.6	215.7	217.9
	E	208.6	209.8	208.7	211.5	208.8	214.6
L3	B	212.4	213.0	212.2	213.9	212.2	215.8
	E	202.0	203.5	202.0	205.6	202.1	209.6

Table 4.9 *RMS values of the voltages in volt at the begin and at the end of the line before and after an increase of solar irradiation in a rural area. The household load used is 7.5 kVA and the cable cross section is 50 mm^2.*

Phase	**Begin (B) or End (E) of line**	**Small decrease**		**Medium decrease**		**Large decrease**	
		$t<0.4$ s	**$t>0.4$ s**	**$t<0.4$ s**	**$t>0.4$ s**	**$t<0.4$ s**	**$t>0.4$ s**
L1	B	217.2	216.3	216.7	214.2	216.8	212.1
	E	203.3	200.4	203.3	196.7	203.3	189.1
L2	B	212.5	195.3	216.0	206.7	216.0	202.4
	E	201.6	195.3	212.4	188.8	198.3	177.1
L3	B	209.3	204.3	208.9	201.0	207.9	194.3
	E	194.0	183.7	191.6	176.8	194.1	162.8

Table 4.10 *RMS values of the voltages in volt at the begin and at the end of the line before and after an increase of solar irradiation in a suburban area. The household load used is 7.5 kVA and the cable cross section is 50 mm^2.*

Phase	**Begin (B) or End (E) of line**	**Small decrease**		**Medium decrease**		**Large decrease**	
		t<0.4 s	**t>0.4 s**	**t<0.4 s**	**t>0.4 s**	**t<0.4 s**	**t>0.4 s**
L1	B	219.9	219.4	219.5	218.8	219.5	218.1
	E	216.6	215.4	215.3	214.2	215.3	212.1
L2	B	219.4	217.5	219.5	217.0	218.8	215.3
	E	218.1	213.5	217.0	212.1	213.8	208.7
L3	B	217.3	215.8	216.3	214.0	215.9	212.2
	E	210.3	208.8	209.6	206.2	211.0	202.1

4.4 Influence of household load for different weather conditions

Only results of rural and suburban areas are simulated regarding the influence of household loads for different weather conditions in table 4.11. Therefore, voltages at the begin and end of each power line are simulated for each combination of household loads from 0 kVA, 2.5 kVA to 5 kVA and solar irradiations of 500 W/m^2 and 1000 W/m^2. Results with a household load of 7.5 kVA and results for simulations without solar irradiation can be found in earlier mentioned tables.

Table 4.11 provides information that leads to several conclusions. In section 4.2 the influence of the weather conditions is discussed, those conclusions were valid with high electrical household loads. When the household loads decrease, the current flowing from the grid to the consumer also decreases. This has as a consequence that the voltage drop also decreases.

If the household load decreases even further, eventually the PV power production will become higher than the consumed energy. This is when the voltage drops turn into overvoltages. For a fixed value of solar irradiation, the electrical household load plays an important factor in the size of the voltage drop or overvoltage.

This is illustrated in the results. For an irradiation of 500 W/m^2, the highest voltage drop occurs at a load of 7.5 kVA. This situation has the biggest difference between power consumed and power produced. The smallest voltage drop with an irradiance of 500 W/m^2 occurs with an electrical household load of 2.5 kVA. This means that of all simulations, the difference between power produced and power consumed is the least. Since the voltage at the end of the line is still lower than at the beginning of the line, the power produced is still less than the power consumed. This is true for both rural and suburban areas.

Of course, with no electrical household load, there is an overvoltage in both cases. For an irradiation of 1000 W/m^2, the highest voltage drop also occurs at a load of 7.5 kVA, but at a load of 2.5 kVA, there is an overvoltage at the end of the line instead of a voltage drop. This means the power produced with a solar irradiation of 1000 W/m^2 is higher than the power consumed. This is expected as the PV installation is 3,750 Wp and 1000 W/m^2 is irradiance at which the PV modules produce the most power.

So for different solar irradiation levels, the turnover point from voltage drop to overvoltage vary. The higher the solar irradiation is, the higher the electrical household load is for this turnover point. This is because the power production is, logically, higher for a higher solar irradiation.

Table 4.11 RMS values of the voltages in volt at the begin and at the end of the line for different combinations of household loads and irradiation values in rural and suburban areas.

Household load (kVA)	Irradiation (W/m^2	Line	Begin (B) or End (E) of line	Rural area	Suburban area
0	500	L1	B	229.1	228.6
			E	231.9	229.4
		L2	B	230.1	228.6
			E	231.9	229.7
		L3	B	229.1	228.8
			E	230.5	229.8
	1000	L1	B	232.5	228.8
			E	239.3	230.8
		L2	B	234.2	230.1
			E	240.4	232.7
		L3	B	237.1	231.0
			E	244.6	232.7
2,5	500	L1	B	225.0	225.3
			E	218.8	224.0
		L2	B	223.1	224.8
			E	213.2	223.6
		L3	B	220.7	223.6
			E	207.5	220.6
	1000	L1	B	226.6	226.1
			E	223.2	226.2
		L2	B	225.2	226.1
			E	222.0	226.6
		L3	B	224.1	225.3
			E	220.6	225.5
5	500	L1	B	218.2	222.1
			E	199.4	218.8
		L2	B	208.8	220.1
			E	191.0	216.8
		L3	B	203.0	218.8
			E	179.4	213.2
	1000	L1	B	220.7	222.7
			E	206.9	220.9
		L2	B	213.2	222.0
			E	202.2	220.6
		L3	B	209.3	220.7
			E	192.7	217.0

4.5 Influence of PV module temperature

For the influence of the temperature of PV modules on the overvoltages and voltage drops, simulations only have been executed for rural areas. Tables 4.12 and 4.13, in combination with results from table 4.1, can be used to determine the influence of the surface temperature of PV modules on voltage drops and overvoltages.

Independent of the type of area, figure 4.1 shows how the current-voltage and power-voltage characteristics change in function of PV module temperature. This figure is based on a PV installation of 15 series connected Trina Solar TSM-250PA05.08 PV modules which is used in the simulations. The characteristics are made for an irradiation of 1000 W/m^2. Since one PV module has a power output of 250 Wp, the total power output of the PV installation should be 3.750 W, which is true with a module temperature of 25 °C.

Table 4.12 *RMS values of the voltage at the beginning (near transformer) and at the end of all three phases with 7.5 kVA household loads and a 50 mm^2 distribution cable for 500 W/m^2 and 1000 W/m^2 solar irradiation in a rural area for a PV module temperature of 0 °C .*

Solar irradiation (W/m^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
500	L1	214.7	196.7
	L2	206.8	189.1
	L3	201.3	177.0
1000	L1	217.0	203.6
	L2	211.4	200.8
	L3	207.2	190.5

Table 4.13 *RMS values of the voltage at the beginning (near transformer) and at the end of all three phases with 7.5 kVA household loads and a 50 mm^2 distribution cable for 500 W/m^2 and 1000 W/m^2 solar irradiation in a rural area for a PV module temperature of 50 °C .*

Solar irradiation (W/m^2)	**Line**	**V_{LN} near transformer (V)**	**V_{LN} at end of the cable (V)**
500	L1	214.2	195.1
	L2	205.0	185.4
	L3	200.1	173.2
1000	L1	216.6	201.5
	L2	210.3	198.3
	L3	205.6	188.1

Results indicate that higher surface temperature of the PV module results in a higher voltage drop. This conclusion is made based on the fact the electrical household load is 7.5 kVA and it is correct as long as there is a voltage drop. As soon as the voltage drop turns into an overvoltage, the overvoltage will be reduced at higher temperatures of the PV modules.

PV cells produce less power with increasing temperature because the band gap is reduced. This reduced band gap reduces the open-circuit voltage and MPP of the PV cell, leading to a smaller power production. Between 0 °C and 50 °C the difference in open-circuit voltage is approximately 100 volt over 15 PV modules. The influence of temperature on the short-circuit current is the opposite. However, the influence on the current is only a minor effect and cannot compensate the difference in power output at all. .

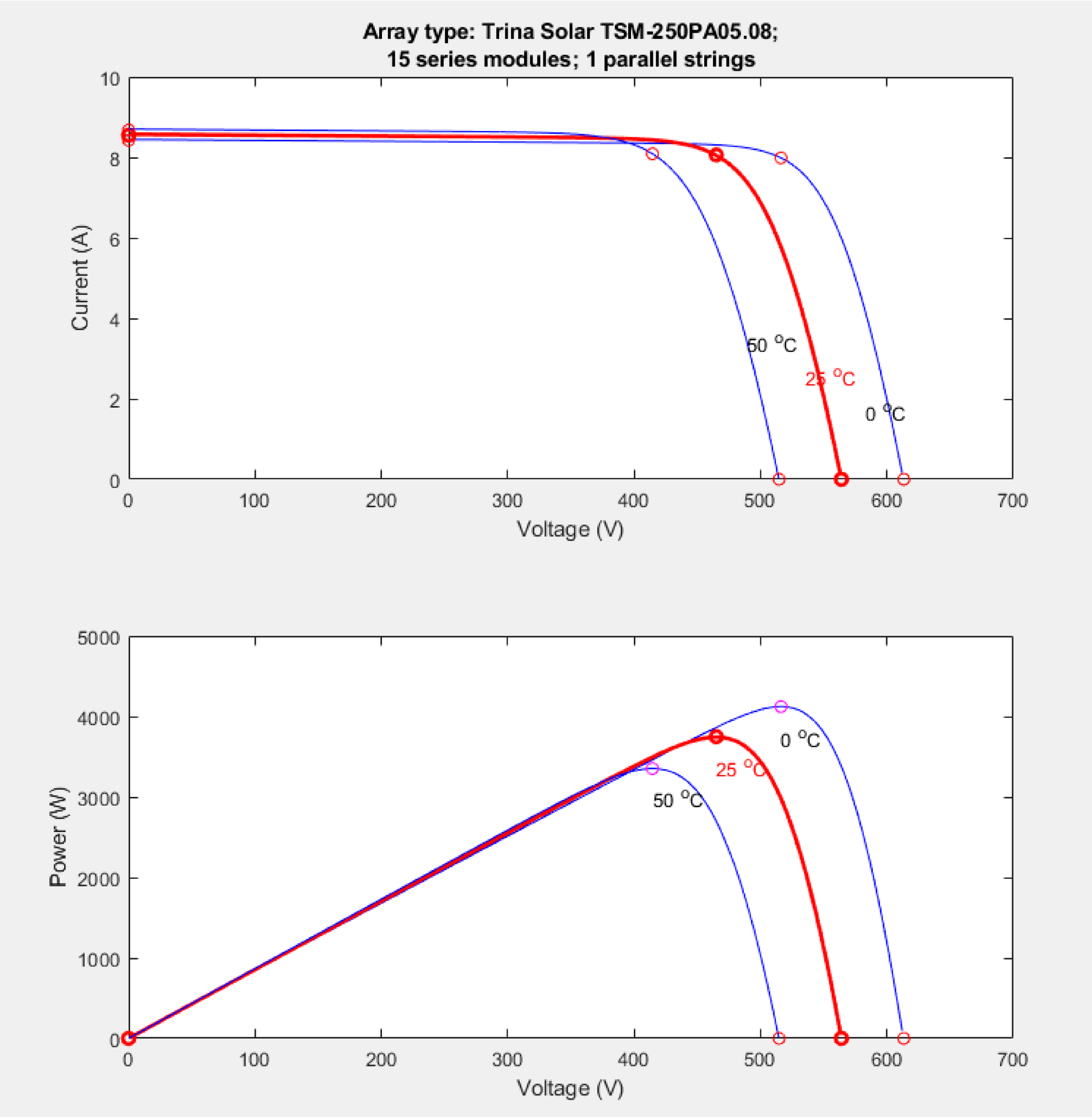


Figure 4.1 *Current-Voltage and Power-Voltage characteristics for a PV installation consisting of 15 series modules of Trina Solar TSM-250PA05.08 for different suface temperatures of the modules and an irradiance of 1000 W/m*^{2}.

5. CONCLUSIONS

The aim of this thesis was to study power quality issues caused by solar PV power generation. Power quality is a field of study that covers a lot of problems, but this thesis was focused on overvoltages and voltage drops. Other possible issues involve PV installation induced harmonics and transients induced by varying condition. This last has also been discussed very briefly in this thesis. To do this, a simulink model of a single-phase PV module was used and implemented in three different cases.

Three cases that each represent a typical residential area are studied. The first one is a rural area. Households are widely spread and have a long distribution cable that connects them to eachother. In rural areas, houses usually have enough space to place the ideal amount of PV panels. The second type of area is the suburban area. Distances are shorter, but houses usually still have enough space to install the ideal amount of PV panels. The last area is the urban area, where distances between houses are very short and only some of the households have enough space to install enough PV panels.

This thesis states that rural areas are the most vulnerable for voltage drops in general and overvoltages caused by solar PV power generation. Grid impedance is the most important element and rural areas have worse grid parameters than urban areas for this element. Long distances and relatively small cross sections of cables cause a high grid impedance. Shortening lengths is unfortunately no option, but installing distribution cables with a bigger cross section could reduce the grid impedance drastically.

Different weather circumstances can have a huge impact on overvoltages and voltage drops in grids with a high penetration of PV panels. In this thesis a reduction of 40 % of the voltage drop is mentioned. This percentage is only illustrative, but still shows the importance. This thesis does not grant quantitative results, it only shows that voltage drops can be reduced drastically, how much exactly is different for each case.

Rapid change in solar irradiance does not affect the steady state values of the obtained RMS voltages. The transient effects are affected by it. When solar irradiance skyrockets over a short period, temporarily peak values of the AC signal are higher than the normal peak values. The hight of the peaks is the highest when the irradiance difference is the biggest. The reached peak value also depends on the momentary value of the voltage, peak values are different when the momentary voltage is close to the steady state peak value or when it is close to 0 volt.

Temperature of the PV modules also plays a role in the PV power production. The higher the temperature, the lower the power yield. This can be a good thing for grid operators. In winter, when it's cold and a lot of electrical energy is consumed, PV cells can produce relatively more energy, due to the cold. They would produces less energy if it would be warmer and with the same amount of solar irradiation.

Other power quality issues that may be evaluated in the future or other theses could focus on the harmonics induced by PV power generation. Also the rapid change of weather conditions, which have not been treated in detail in this thesis, could be the topic of follow-up studies.

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